A HEAT RADIATION TELESCOPE AND THE MEASUREMENT OF THE INFRARED EMISSION OF THE ATMOSPHERE

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1. *Historical note.*—The instruments which have been constructed to measure sky radiation are of two types. First, there are devices which measure the total radiation coming in from the sky at all angles. In their simplest form they consist of a black horizontal plate exposed to the sky and mounted next to another plate which is either shielded from the sky or has metallic reflectivity; th difference in temperature of the two plates is measured by means of a thermocouple. In order to avoid condensation on the black plate during the night and also in order to minimize the effect of turbulent heat conduction through the air, it is advantageous to balance the temperature difference of the two plates by heating the colder plate electrically until the temperatures of both plates are equal. The square of the heating current measures the amount of heat supplied to the cold plate per unit time which in turn is equal to the heat lost by radiation. Instruments of this type have been constructed by Ångström, Albrecht, Ramanathan, and others. (1) In the melikeron (honeycomb) constructed by Aldrich of the Smithsonian Institution (2), the black plate is replaced by a grid formed by blackened strips of thin metallic foil. The strips are standing on edge and the honeycomb thus resulting is "blacker" than a simple horizontal plate since any radiation scattered by the absorbing surfaces has a higher probability of hitting an opposite surface than of escaping back to the sky. Two instruments of this type have been in use by the United States Weather Bureau.

The second type of radiation instrument measures only the radiation coming from a given part of the sky. In its simplest form the instrument consists of a black plate located at the bottom of a box without top; and the effective radiation comes only from that fraction of the sky which is visible to the black plate. Usually the box is more or less tapered toward the lower end. By means of this arrangement the intensity of the incoming sky radiation can be measured as a function of the angle of elevation. Instruments of this type have been built by Dines (3) Dubois and Linke (4) and F. A. Brooks (5). Linke (4) has furthermore shown that the following approximate relation holds for the effective radiative heat loss E of an unobstructed horizontal black plate, E being expressed as fraction of the total black body radiation emitted by the plate:

$$E = \frac{e_0}{1 + 1.66 \log_{10}(e_1/e_0)}.$$

Here e_0 is the fractional radiative loss toward the zenith; $e_0 = (b-s)/b$ where b is the black body radiation emitted by the plate into a solid angle around the zenith and s is the radiation received from the sky in the same solid angle and e_1 is the same quantity for a direction inclined by 60° relative to the zenith. Since this formula is found

to yield E with a high degree of accuracy, it is practically sufficient to make two readings with a shielded instrument in order to obtain the total sky radiation. Hence, with regard to the quantitative determination of the total incoming radiation, there is no distinct advantage in the use of any one type of instrument. The instrument with a limited view will of course have a smaller change in temperature than the one with complete exposure and this necessitates the use of a galvanometer of higher sensitivity. It seems however that in protecting the plate from atmospheric eddies by means of the surrounding box a smoother operation of the instrument is insured in spite of the more sensitive galvanometer required.

2. *The instrument.*—In our instrument the receiving black plate and a compensating plate are located in the focal plane of a concave mirror (fig. 1), a construction first used by P. Dubois (6). The "plates" are tiny silver disks. The mirror was obtained by aluminizing (7) one side of a concave lens of 7.5 cm diameter; and it has a focal length of 10 cm. The tube of the telescope has an overall length of 44 cm. The disks are mounted inside a central tube of 1.2 cm diameter which also contains an eyepiece of a design that may be recognized from figure 1. The observer who looks into the eyepiece sees the disks simultaneously with the object toward which the telescope is directed. The central tube and eyepiece are fastened to a tube which slides inside the main tube of the telescope and focal adjustment for objects of various distances is made by means of a screw drive which, for the sake of clarity, has been omitted from figure 1. The ribs holding the central tube and this tube itself are of copper, while the remainder of the instrument is of brass. The use of copper insures a rapid equalization of temperature differences in the central part. One of the three copper ribs holding the central rod is especially heavy; it leads to a copper block which projects to the outside through a slot in the outer tube and which contains the bulb of a sensitive thermometer. By means of this connection it is possible to obtain accurately the temperature of the central tube from a reading of the thermometer. The instrument is suspended in a rectangular gavel and it can be rotated around a horizontal and a vertical axis, the finer regulation being made by means of adjustment screws. A vertical protractor is provided to be used for sky radiation measurements. The whole instrument and gavel are nickelplated in order to minimize radiative heating or cooling of the instrument. The instrument together with tripod and switch-boxes can be folded to fit into a wooden case the size of an average suit case.

The receiving unit, as it appears on looking through the eyepiece, is shown in figure 2. The receivers are two silver disks 1.2 mm. in diameter and 0.13 mm. thick. They are blackened with zinc black deposited by sputter-
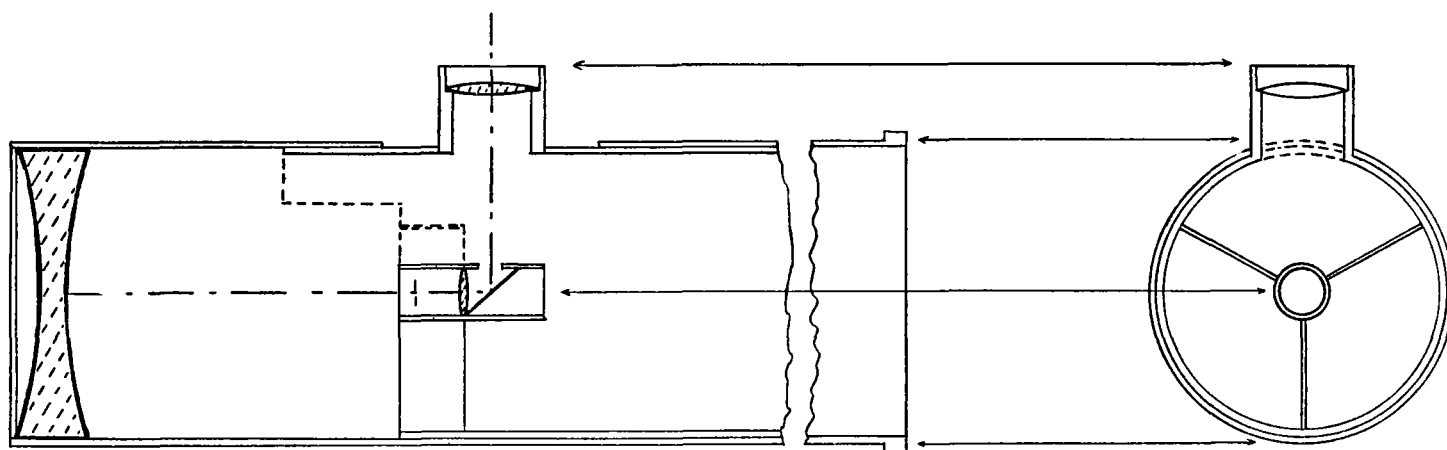
FIGURE 1.

ing under reduced pressure after the method of Pfund (8). This method yields extremely black surfaces; according to tests which extend from the visible region to a wavelength of 11 μ it is practically completely (98 to 99 percent) black over this whole interval, and it can, therefore, in all probability, be assumed to be black for the remainder of the spectrum. While this method of blackening is not applicable to open surfaces, as the black can be wiped off easily, it has distinct advantages in encased receivers. Its heat conductivity is much higher than that of soot and other conventional forms of optical black; this minimizes the temperature gradient across the coat of blackening, and the effective radiative temperature of the black surface will be nearly the same as that indicated by the thermocouple.
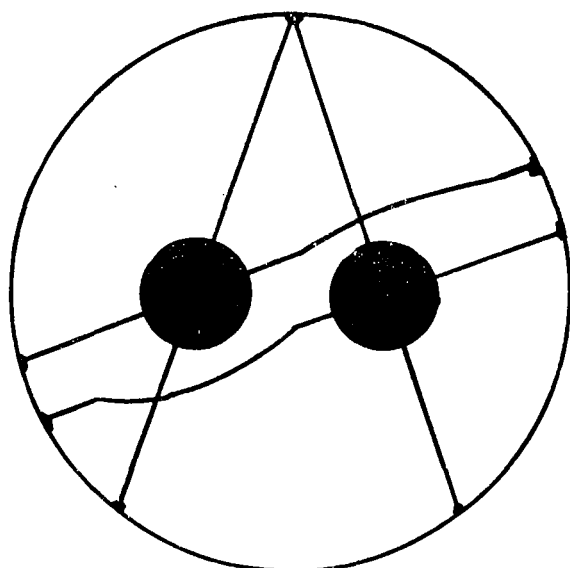

FIGURE 2.

Two wires are seen crossing each disk in figure 2. One is a thermocouple while the other is a heating wire by means of which the cooling of each disk can be compensated by electrical heating. The thermocouple consists of a constantan-manganin combination, the wires being 0.03 mm. thick. While this element has only 40 microvolts per degree, an electromotive power considerably less than some other thermoelectric combinations, the wires are drawn wires and have an extremely high mechanical stability. Furthermore, the resistance and the electromotive force of this couple are very insensitive to temperature changes. The couples are soldered to the silver disk. The two couples together form the V-shaped figure seen in figure 2; they are used in series with opposite polarities, measuring thus the temperature difference between the disks. The constantan wires form the tip of the V, while the manganin wires are at the open ends. If the two couples are used in series in this manner, the cold junctions are formed by the two copper-manganin combinations at the open ends; as the thermoelectric force of this combination is exceedingly small, the influence of a temperature gradient between the cold junctions is greatly reduced. An outside connection of the constantan junction is provided, however, so that each couple may be used individually if desired. There is found to be an appreciable thermal coupling of the two disks by conduction through the air; if one of the disks is irradiated, the other disk will change its temperature by about one third of the change of the first disk.

The heating wires are made of constantan wire of the same thickness. A tiny speck of brass foil is soldered to their middle and this foil is pasted to the back of the silver disk with glyptol. The heating circuit is everywhere completely insulated from the thermocouple circuit.

Each of the thermocouples has a resistance of about 5 ohms. The galvanometer used was a Leeds and Northrup high-sensitivity galvanometer with the following characteristics: Internal resistance 19 ohms, critical damping resistance about 10 ohms; with critical damping resistance in series and with the scale at 2 m. distance, as the instrument was normally used, the sensitivity is about 2 mm. per 10^{-7} volts. The telescope is connected with a control unit by a cable of 5 m. length. The control unit consists of a set of switches for the thermocouple circuit and a switchboard with rheostat for the heating circuit. The heating wires are shunted by a very low resistance so that the total current flowing in the heating circuit is of the order of several hundred milliamperes; it can be read from an ordinary Weston milliammeter. The voltage is supplied by a 2-volt storage battery.

3. *General tests.*—The instrument is calibrated in terms of the compensating current by making one disk look into a bottle with liquid air. For this purpose the instrument is provided with an attachment tube 30 centimeters long and of about the same diameter as the main tube of the telescope. The attachment is closed by an aluminum plate with an excentric hole; and if the instrument is focused upon this plate, the image of the hole is seen to be covered by one disk (the image of the hole being somewhat larger than the disk) so that this disk exchanges

radiation with the liquid air while the other disk receives radiation only from the reflective surface of the aluminum. The second disk may therefore be assumed to be in radiative equilibrium with and at the same temperature as the body of the telescope. For calibration the interior of the instrument is filled with air which is dry and free of carbon dioxide. Such air can be produced by letting liquid air evaporate, warming it to room temperature and then leading it to an inlet provided at the attachment. It is found that after about 20 minutes all the moisture is removed and the reading of the instrument becomes constant under continued flow of the dry air. The deflection of the galvanometer for liquid air and 20° room temperature was about 170 millimeters with the scale at 2 meters distance. All galvanometer readings were made to a tenth of a millimeter. It was found that the reading did not depend upon the angle under which the surface of the air is sighted. This result was interpreted to mean that there could be no appreciable amount of radiation of room temperature reflected at the surface of the liquid air. As a check the temperatures of several mixtures of dry ice and alcohol, ranging between −60° C. and −20° C., was measured. The radiation calculated by Stefan's law from the temperature of the bath as indicated by a thermometer and the radiation measured by the instrument agreed always to within 1 percent. Temperatures close to room temperature can readily be measured; the observed deflection is of the order of 2 millimeters per degree temperature difference between the instrument and the object. If the radiation of extended objects, such as water, snow, or the sky is to be measured, it is convenient to use the attachments described before. The effective radiation then forms a bundle converging toward the instrument with an opening angle of about 8°. To measure the radiation from smaller objects it is necessary to focus the instrument upon them and to have the second disk covering an object of known temperature. For this a round piece of paper was used which assumes the temperature of the surrounding air. If the object is near the instrument, the paper is put at approximately the same distance as the object; for distant objects it is sufficient to have the paper at a distance of about 15 feet. We might note here that any change of focus produces a change in illumination of the disk and hence measurements of objects at different distances must be corrected for this change in order to be comparable. This purely geometrical quantity can readily be calculated from the distance of the object; it was also directly verified by a set of check measurements. In all cases of temperature measurements of distant objects a correction has also to be applied for the emission of water vapor and carbon dioxide in the optical path between the instrument and the object. This correction may be taken from figure 4 and is discussed below.

In order to study the behavior of the instrument in field measurements, it was set up on the flat roof of the California Institute of Technology during several evenings. The attachment was removed so that the telescope was open to the air at one side. It can be closed by means of an aluminum shutter. It is found that if the instrument is either closed by the shutter, or if it is open and both disks are simultaneously pointed at the same wall or at the sky, there will be a zero deflection of the galvanometer which usually keeps between 2–5 millimeters, but which changes only very slowly in time. This effect is mostly due to a temperature gradient established across the central tube of the instrument after the latter has reached a steady thermal state. If a measurement is made by reading first the zero with closed shutter, then

opening the shutter for about 45 seconds and then reading the zero again after the shutter has been closed for another 45 seconds, there is usually only a difference of 1–3 tenths of a millimeter between the two zero readings, which corresponds to only a fraction of a percent of the black body radiation at air temperature. There seems to be little difference in the stability of the instrument whether the shutter is open or closed. Conditions in southern California are of course very favorable, the air being rather quiet, but it may be concluded that if the instrument is used for sky radiation measurements with the attachment in place, which gives much additional protection, it will give good results even when a strong wind is blowing. In order to avoid fluctuations due to adiabatic compression of the air such as produced by gusts in the open air or by the opening and shutting of a door in a room, the disks were made much heavier than is customary for thermocouple receivers so that they take about 45 seconds to reach full equilibrium (the sensitivity at equilibrium is however not affected hereby) and they were made as rigorously alike as possible by cutting them in a lathe from a silver foil. It is found that when both disks are exposed to liquid air simultaneously in a quiet room, the resulting galvanometer deflection is only a fraction of a millimeter.

While in most respects the instrument met expectations, it was found that the use of a compensating heating system is not entirely advantageous in this type of instrument.
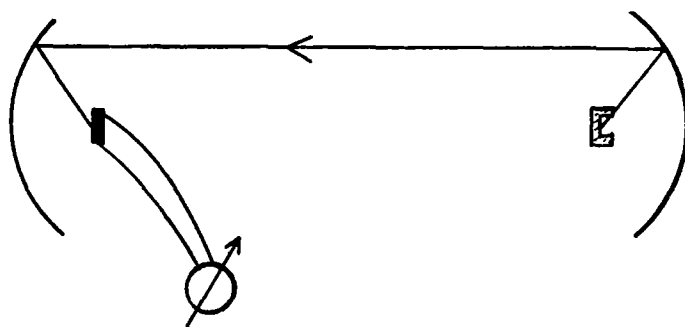

FIGURE 3.

It was originally thought that it would supersede the necessity of recalibrating the instrument and galvanometer in position each time, but this expectation was not fulfilled. This is probably at least in part due to the fact that the shunts which parallel the heating wires are extremely low resistances and unless they are soldered with extreme precision they are liable to change slightly under mechanical shaking or temperature changes. The heating system is somewhat clumsy in actual operation. It is contemplated to remove it in the future. For accurate measurements the instrument must be calibrated each time; in the experiments described below, it was recalibrated with liquid air at the beginning and end of each working evening. It was found that for ordinary field work, such as sky radiation measurements, it is quite sufficient to calibrate by aiming into a thermos bottle filled with water of a temperature about 30°–40° C. above that of the instrument and correcting for the absorption of the water vapor in the optical path between the warm water and the receivers.

4. *The emissivity of water vapor.*—While the instrument can be used to measure sky radiation and the radiative temperature of distant objects, it was constructed for the immediate purpose of determining the emissivity of moist air by the Hottel method (8). The principle of this method is indicated diagramatically in figure 3. The system at the left of figure 3 represents the receiving instrument. To

the right is another concave mirror at the focus of which a black body is placed that is kept at the temperature of liquid air. The instrument is focused upon this mirror in such a way that one of the disks will be seen to cover the magnified image of this black body. Now the radiation originating from the latter is extremely small due to its low temperature; it amounts to only a percent of the black-body radiation at room temperature. The radiation falling upon the disk is then equal (apart from this small amount emitted by the black body) to the *emission* of the column of moist air traversed by a ray originating at the black body and ending at the receiving disk.

The mirror used was a standard army searchlight mirror of 75 centimeter diameter [1] which was aluminized at the front side.[2] The black body consisted of a hollow piece of copper connected to a piece of heavy copper tubing which emerges from a thermos bottle filled with liquid air. It was found by tests that, if the bottle is freshly filled, the radiative temperature of the black body as measured by the instrument is indistinguishable from that of liquid air. By means of this set-up it was possible to measure the emission of moist air for distances between the insturment and the searchlight mirror ranging from 3 meters up to 50 meters. Smaller distances were measured by looking directly into a flask filled with liquid air. The smallest distance measured was 13 centimeters; this was obtained by filling the instrument and the attachment with dry air and holding the free surface of the liquid air at 13 centimeters from the opening of the instrument. Stirring the air with a fan did not change the reading and it was therefore assumed that the dry air streaming out of the opening of the instrument was distributed so rapidly by mixing that it did not reduce the amount of moisture in this path.

In order to cover distances longer than 50 meters the instrument was combined with an astronomical mirror [3] of 54 centimeters diameter and 10 meters focal length to form a telescopelike arrangement. The magnifying power of the instrument was thereby increased almost sevenfold. Optical paths between 20 and 120 meters were set up under an open arcade on the campus. The astronomical mirror was then mounted on a concrete block in a park opposite the campus and a maximum optical path of 315 meters was obtained.

As is well known, the moisture near the ground has an appreciable vertical gradient due to turbulence and evaporation. The optical path was about 5 feet above the ground and it was technically difficult to go higher. The following method was therefore adopted to measure the moisture content in the path. A glass bottle holding 20 liters was evacuated and if a stopcock was opened, air would stream into the bottle. The air would first go through a collecting tube, then through a U-tube filled with phosphorous pentoxide and finally through a capillary to reduce the rate of flow. The phosphorous pentoxide was weighed before and after each filling of the bottle. The bottle was mounted on a toy truck and an assistant would carry it along the path holding the collecting tube as accurately as possible at the height of the optical path. By using two or three bottles in turn it was possible to obtain 5–6 representative samples of the moisture during each evening at which a measurement was made. The measured values of the moisture show surprisingly large fluctuations which cannot be ascribed to errors of measurement, but represent almost certainly an eddy structure of the air. Fortunately the infrared emissivity is very insensitive to small changes in moisture content.

Our results are represented in figure 4, where the emissivity of water vapor is expressed in percent of the black body emission for 20° C. Abscissa is the logarithm of moisture in grams per cm.[2] The carbon dioxide emissivity as measured by Hottel and Mangelsdorf (9) with the same method is also given, and the fraction of the emission due to the carbon dioxide in the path was subtracted from the experimental results. Corrections were also made for the reflectivity of the aluminum surfaces which was determined by separate exper ments (about 3 percent loss per reflexion) and for the deviations of the air temperature from 20°. The latter correction was small, as in all experiments the air temperatures were between 15° and 25°. All the points which were measured are entered in figure 4 with exception of those obtained on the first two evenings where the optical adjustment was found inadequate, and two later points which were quite obviously in error.

These results provide a check on the atmospheric radiation chart constru cted by the writer (10). The dashed curve in figure 4 indicates the water vapor emissivity according to the chart. As the chart gives the radiation of slabs of moist air with horizontal stratification, while our measurements yield the emission of a linear column, the two sets of values are not immediately comparable.
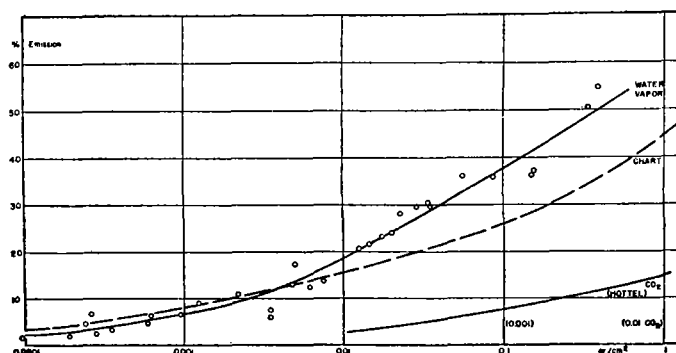

FIGURE 4.

The dashed curve was obtained by taking as optical thickness twice the thickness of the slab indicated in the chart. It is seen that for short paths there is excellent agreement between calculated and observed values. For longer paths there is a rather serious discrepancy, the calculated values being too small by 10 to 15 percent of the black body intensity. This must be attributed to too small a value for the intensity of the 6μ absorption band. As pointed out before (10) the inaccurate knowledge of the strength of this band was the main handicap in getting reliable quantitative information about the effects of radiative transfer in the atmosphere. It is now planned to use these results as a basis for a second, improved edition of the radiation chart. While a number of results derived from the application of the chart (11) must undergo minor changes of a quantitative nature, it is apparent that the discrepancies now revealed are not so pronounced as to necessitate a change of the fundamental results derived from the study of atmospheric radiation. It must appear that the mean cooling in the cloudless atmosphere will still be approximately a linear function of the logarithm of the specific moisture (*l. c.*); only the numerical coefficients will be slightly different. There remains also the general result derived, namely, that the atmosphere is cooled everywhere and is heated nowhere by infrared radiation. The discussion of these conclusions is however not within the scope of the present note.

Finally, our results may be compared to those of similar experiments carried out by Falckenberg (12) which extend over a more limited range of moisture. Falckenberg's values for the emissivity are much higher than ours, for instance for 0.0005 gr/cm² of water he finds 6.7 percent emission, for 0.0015 gr/cm² he has 13.4 percent, and for 0.0075 gr/cm² he has 17.5 percent, the figures referring to the same temperature of 20° for water vapor as ours. On the other hand, we might derive some information from the results obtained by Hottel and Mangelsdorf (9) on steam. The values of the latter work are intermediate between those of Falckenberg and ours. Now general spectroscopic evidence indicates (and this will also be seen from the numerical values in the radiation chart) that between 0° C. and 100° C. the percent emissivity increases with increasing temperature for the thicknesses of moisture considered here. The values for steam ought therefore to lie above our values, as is observed, while an experimental error in Falckenberg's values seems indicated. For the same interval of moisture, Schnaidt (13) has calculated the emissivity on the basis of spectroscopic data partly independent of those used in the construction of our radiation chart and his results are in close agreement (within ±1–2 percent of the black body intensity) with our measured curve.

Conclusion.—The experiments carried out by us seem to indicate that there are a number of advantages in using for the measurement of atmospheric radiation the closed type radiation instrument with a concave mirror. Two ways seem to be open to increase the sensitivity of the instrument. While our mirror covers a solid angle which is about 8 percent of the maximum solid angle of 2π, it should be possible without much difficulty to grind a short focus mirror covering about one-half of the hemisphere. Furthermore multiple junction thermopiles might be used, although it is perhaps difficult to compensate them as well against temperature changes due to adiabatic compression of the air as one can compensate the one-junction type, and the use of the latter might remain more advantageous.

During a clear autumn night an hour-to-hour record was made of the radiative temperature of the foliage of several trees, one of them an orange tree. Simultaneously the radiative temperature of a piece of bare ground and the sky radiation were recorded. While the radiative temperature of the ground was consistently below the air temperature by about 0.8° C. from early evening until sunrise, the temperature of the tree foliage showed an irregular deviation from the air temperature of only a few tenths of a degree, which is within the observational errors. The dew point was however very close to the air temperature during the whole night, so that it is hardly possible to apply this result to the dry polar outbreaks during which the freezing of orchards occurs.

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THE VARIABILITY OF PRECIPITATION

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[Pennsylvania State College, State College, Pa., October 1939]*

In some years on Malden Island, precipitation amounts to 100 millimeters (3.94 inches), and in others to 2,000 millimeters (78.8 inches) and more. The mean of many years amounts to 727 millimeters (28.6 inches). The relative variability is 71 percent.[1] This is the most extreme case on the earth, as far as known. From the geophysical, meteorological, and climatological standpoint, such variations of precipitation are of great interest. The possibility of years with floods, with abundant crops, and of years with famines at the same place indicates great variability, the explanation of which is a problem for the above sciences.

In the present paper the variability of precipitation is discussed, from a statistical point of view.

If the mean yearly sum is called $\overline{p}$ and the individual yearly sum p_i, then

$$p_i - \overline{p} = \epsilon_i.$$

The expression

$$\frac{\Sigma \epsilon_i}{n} = v_a$$

is called *absolute average variability.* It is clear that v_a must increase with $\overline{p}$. The geographical distribution of v_a would therefore give the same picture as the precipitation map itself. Hence v_a should be expressed in percent of $\overline{p}$. The quantity

$$v_r = \frac{100 v_a}{\overline{p}}$$

is called the *relative variability;* it appears to be the best measure of variability.

The geographic distribution of v_r is so remarkable that a detailed investigation is desirable.

1. THE ABSOLUTE VARIABILITY

The places with yearly precipitation 0–200, 201–400, 401–600 millimeters, etc. (0–7.9, 7.91–15.7 inches, etc.), were grouped. For each group both the mean yearly sums ($\overline{p}$) and the absolute variabilities (v_a) were averaged. If the average variabilities are plotted against the mean precipitation (table 1), a linear connection is clearly indicated. The data may be closely represented by the equation:

$$v_a = 36 + 0.13 \overline{p}$$

The differences "observed–calculated" (o–c) appear in the last column of table 1. As the values of v_a and $\overline{p}$ are derived from observations over the whole earth, the above equation may be regarded as the normal relation.

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